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Holocene Glaciation of the Arrigetch Peaks, Brooks Range, Alaska

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ABSTRACT. Eleven cirque glaciers and associated deposits within the granitic Arrigetch Peaks of the west-central Brooks Range face north, minimizing insolation. Shading by surrounding mountainous terrain decreases insolation on these landforms even more significantly, favoring the formation of glacier-cored moraines. Comparison of glacier photographs taken in 1911, 1962, and 1979 reveals a record of decelerating recession. Geomorphic and lichenometric mapping suggests at least three to possibly eight phases of Holocene glacial expansion. These date between ~ 5000 and 300 yr B.P., based on the application of a central Brooks Range *Rhizocarpon geographicum* growth curve.

RÉSUMÉ. Dans les hauts plateaux granitique Arrigetch situés dans la partie centre-ouest de la chaine Brooks, on retrouve onze cirques glaciers et leur dépots orientés vers le nord, minimisant ainsi l'ensoleillement. L'ombre produite par les terrains montagneux limitrophe diminue cet ensoleillement de façon encore plus marquée favorisant ainsi le développement de moraines faites d'un noyau de glace. Une comparaison des photographies du glacier en 1911, 1962 et 1979 montre un ralentissement de son recul. La cartographie géomorphique et lichénométrique suggère au moins trois et possiblement jusqu'à huit phases d'expansion glaciaire lors de l'Holocène. En considérant la courbe de croissance de *Rhizocarpon geographicum* dans la partie centrale de la chaine Brooks, ces expansion datent d'entre ~ 5000 et 300 ans A.A.

Traduit par Ian Badgley, Université du Québec à Montréal.

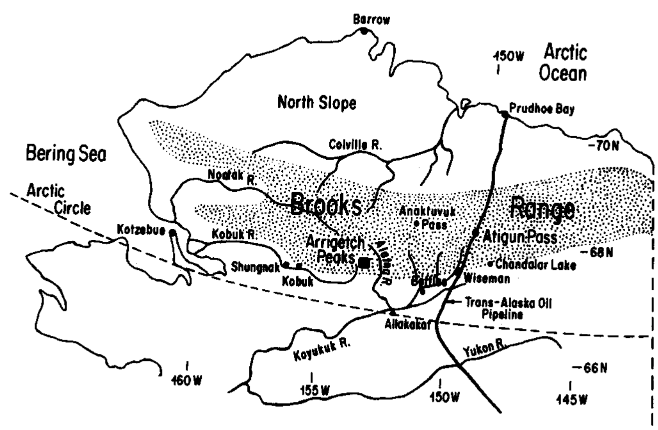

FIG. 1. Location map of northern Alaska.

INTRODUCTION

The Arrigetch Peaks, an array of jagged granitic horns and arêtes between deeply-incised cirques and glacial troughs, occupy an area of about 110 km² on the south flank of the Brooks Range (Fig. 1). Summits rise to altitudes of 1800 to 2150 m, some to heights of 1200 m above valley floors. More than 40 cirques surround individual peaks and line the north-facing walls of glacial troughs; 11 of these basins are occupied by glaciers up to 2.2 km long (Fig. 2; see also U.S. Geological Survey, unpub. data 1978). Drainage toward the northwest, north, and east is via tributaries of the Alatna River, which flows south into the Koyukuk. Drainage southwest and south is through headwaters of the Kobuk River west into Kotzebue Sound. The peaks lie entirely within continuous alpine permafrost (Ferrians, 1965), and lower slopes and valley floors bear a cover of alpine tundra. The lowest valleys extend down to the limit of the boreal spruce forest, which reaches about 600 m altitude in this sector of the Brooks Range. The Arrigetch Peaks consist of granitic orthogneiss of Middle Devonian age (Nelson and Grybeck, 1980). The strength and durability of this massive crystalline rock enable it to support nearly vertical slopes that protrude as much as 1000 m above the more erodible limestone, shale, and schist of the surrounding terrain.

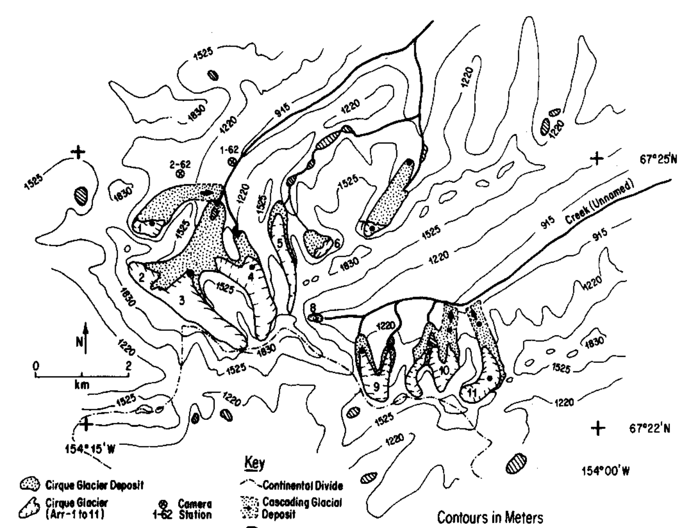

FIG. 2. The Arrigetch Peaks cirque glaciers and their associated deposits. Arr-5, -6, and -8 were not studied in the field.

Glaciers in the Arrigetch area are of particular interest because of their climatic setting, their long photographic record, and the value of the Arrigetch granitic rocks as erratics that indicate the extent and distribution of Pleis-

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tocene glaciations. The moisture regime of the Arrigetch area appears to be transitional between the wetter maritime conditions of the western Alaskan coast and the relatively dry continental climate of interior Alaska. Winter snowfall is heavier and snow-avalanche activity is greater than farther east in the Brooks Range (Hamilton, unpub. data 1980). Summers are short and generally cool; coastal storms commonly invade from the west via the broad Noatak and Kobuk valleys. Although records are sporadic and difficult to compare, climatic data from small villages at low altitudes along the south flank of the range show a general eastward decline in annual precipitation (Table 1). In addition, summer temperature, annual snowfall, and total precipitation decrease northward across the Brooks Range (Johnson and Hartman, 1969:62-79; Haugen, 1979). Cirque glaciers (1750 m) at Atigun Pass, 225 km east-northeast of the Arrigetch Peaks (Fig. 1), have been monitored for precipitation since 1977 (Calkin and Ellis, 1980). Annual precipitation here ranges between 400 and 700 mm, of which about 50% is snow. These climatic factors cause Pleistocene and Holocene snowlines, abandoned cirques, moraines of late Holocene age, and modern glaciers to increase in altitude north- and eastward from the Arrigetch Peaks (Porter, 1966; Péwé, 1975:26-32; Ellis and Calkin, 1979; Hamilton, 1978, 1979, unpub. data 1980).

TABLE 1. Average annual precipitation recorded in valleys along south flank of the central Brooks Range[a]

Region	Stations (with altitudes in meters)	Average annual precipitation (millimeters)
Middle Kobuk	Kobuk (~50); Shungnak (~50)	400 - 430
Middle Koyukuk	Allakaket (105); Bettles (189)	330 - 360
Upper Koyukuk	Wiseman (336)	280 - 300
Upper Chandalar	Chaldalar Lake (555)	230 - 280

[a]U.S. Weather Bureau (1915-1979)

Recorded observations of glaciers in the Arrigetch Peaks date to 1911, when Philip S. Smith of the U.S. Geological Survey explored Arrigetch Creek and photographed the glaciers at its head (Smith, 1912, 1913:35, 106). The two unmarked stations from which Smith took his photographs were relocated in 1962; the glaciers were rephotographed and the stations marked with cairns (Hamilton, 1965a).

Most valleys of the south-central Brooks Range were free of Pleistocene glaciers by about 10 700 yr B.P., when streams generally were incising through glacial deposits to approach their modern levels (Hamilton, 1980a). Regrowth of cirque glaciers later in the Holocene was assigned to the Fan Mountain Glaciation by Detterman *et al.* (1958). Later studies by Holmes and Lewis (1965), Porter (1966:66-70), and Hamilton (1978, 1979) suggested that Fan Mountain events represent the late Holocene Neoglaciation, and that it could be subdivided into two phases. Recent lichenometric and radiocarbon dating in cirques near Atigun Pass suggests that the histories of cirque-glacier fluctuations in the central Brooks Range is more complex, and that many cirque deposits are older, than previously supposed (Calkin and Ellis, 1980).

In the following sections we describe the glaciers of the Arrigetch Peaks and evaluate their climatic and topographic controls. Sequential photographs covering a 68-year interval were used to determine the time required for lichen colonization and to test assumptions about substrate stability. We apply the lichen growth curve for the Atigun Pass area to Arrigetch lichens in order to derive a preliminary Neoglacial chronology for the Arrigetch Peaks.

METHODS

In the field we mapped deposits associated with eight of the 11 Arrigetch glaciers and analyzed maps and photographs of the whole area. Planimetry for our lichenometric maps and Figure 2 was based on oblique photographs and on the U.S. Geological Survey 1:250,000 Survey Pass sheet. Altitudes for our study were taken from the topographic sheet, which displays contour lines at 200 ft (60 m) intervals. The accuracy of these altitudes is estimated at ± 60 m. Altitudes for each glacier were measured at the topographic midpoint of ice that was relatively debris-free. Altitudes for their downslope debris lobes were measured at the crest of the debris terminus or at cirque thresholds for cascading deposits (Fig. 2). Orientations of glaciers, cirque headwalls, and debris snouts were plotted to the nearest 10°. The mean of these orientations or the vector resultant was derived by vector summation (Evans, 1977). The concentration of orientations (aspects) along this vector resultant, termed the vector strength (K), represents the degree of asymmetry for the distribution. As defined by Evans, extremely asymmetric distributions have K = 80-100%, and strongly asymmetric distributions have K = 60-80%.

The shadowing effect of surrounding mountainous terrain on cirque glaciers and their deposits was initially analyzed in the field by plotting the horizon at each of 13 sites (Fig. 2). These horizon surveys were made at 015° increments (24 horizon inclinations per site) with a Brunton compass attached vertically to a tripod. Each landform's horizon was then superimposed upon the sun's 24-hour path at +20° declination (~24 July) to determine the times of sun appearance and disappearance. This solar path (List, 1951) was chosen to best characterize the glacier ablation period.

Superimposing the landform's horizon upon the sun's path, as it would be on 24 July, allowed us to establish the *duration* of direct solar radiation received at each site during a typical part of the ablation season. The amount of direct radiation *energy* received at each landform during these times of sun appearance was then calculated, and this sum was compared to that measured at lat. 68°N on unscreened, horizontal surfaces under clear skies (Kondratyev, 1973:304-305). This measured amount is treated as the potential unscreened energy and is assigned a value of 100%. The comparison of the actual amount of energy received to this potential energy provided a measure of the reduction in direct solar radiation at each landform due to the shadowing effect of mountainous terrain. A similar study has been carried out on McCall Glacier in the eastern Brooks Range at lat. 70°N (Wendler and Ishikawa, 1974).

Increasing slope inclination in a more northerly aspect also markedly reduces solar insolation (Table 2). The effects of aspect, slope, and terrain screening on insolation were combined to provide a measure of the total direct-radiation energy received at each survey site during a typical part of the ablation season. These energy values were then correlated with landform types.

TABLE 2. Mean daily direct solar radiation energy at lat. 68°N, +20° declination[a]

Slope	Aspect				
	N	NE or NW	W or E	SE or SW	S
10°	99	99	100	102	103
20°	95	94	102	106	107
30°	87	88	104	109	109

[a]Values expressed as a percentage of that received on an unscreened horizontal surface for a given aspect (direction of opening) and slope (L. Williams, written comm. 1979).

Comparison of glacier photographs taken in 1911 (Smith, 1912; Smith and Mertie, 1930), 1962 (Hamilton, 1965a), and 1979 enabled us to assess the stability of lateral and terminal ridges of two glacier-cored moraines. In addition, lichenometric mapping of the bedrock-cored surfaces, deglaciated since 1911 and 1962, provided rates of lichen growth and glacier recession since the last major Neoglacial expansion.

Lichenometric mapping involved the recording of thallus diameters of *Rhizocarpon geographicum* s.l., *R. eupetraeoides/inarense*, *Alectoria minuscula*, and *A. pubescens* on mappable geomorphic units while traversing as much area as possible (see Calkin and Ellis, 1980 for technique and species descriptions). The maximum diameter of thalli with distinct margins and slightly elliptical to circular shape was measured to the nearest 1 mm. Col-

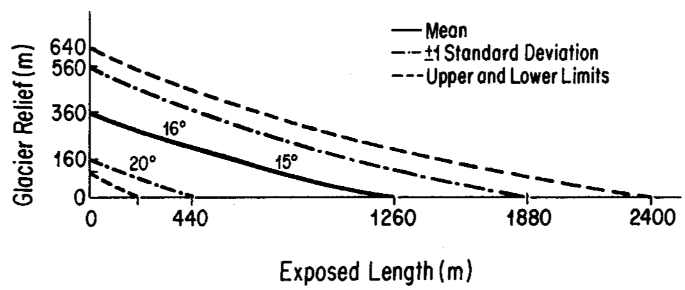

FIG. 3. Generalized profile of 11 cirque glaciers in the study area showing mean relief and length with 67% zone of occurrence (± 1 standard deviation), upper and lower size limits, and slope of glacier surface.

TABLE 3. Planimetric analysis of cirque glaciers and their deposits

Glacier No. (Arr-)[a]	Area of glacier which is relatively debris-free (km²)[b]	Area of glacier debris lobe (km²)[b]	Total area (km²)[b]	Deposit glacier-cored (%)	Deposit lacking lichen cover (%)[c]	Deposit with ≤25 mm *R. geog.* (%)[d]	Deposit type[e]
1	0.20	0.55	0.85	95	75	80	GCM
2	0.25						
3	1.05	1.55	3.80	95	80	85	GCM
4	0.95						
5	0.40	0.15	0.55	. .	. .	. .	BCM?
6	0.10	0.15	0.25	. .	. .	. .	GCM?
7	0.10	0.60	0.70	95	20	30	TRG
8	0.05	0.05	0.10	. .	. .	. .	GCM?
9	0.40	0.20	0.60	70	65	90	GCM & BCM
10	0.50	0.45	0.95	80	75	95	GCM & BCM
11	0.45	0.30	0.75	90	75	95	GCM

[a]See Figure 2.

[b]Areas are rounded to the nearest 0.05 km².

[c]Determined from lichenometric mapping of the 0 mm *Rhizocarpon geographicum* isophyse.

[d]Determined from lichenometric mapping of the 25 mm *R. geographicum* isophyse.

[e]Classification generalized from percent (%) glacier-cored and surface morphometry. GCM = glacier-cored moraine, BCM = bedrock-cored and/or ice-cemented moraine, and TRG = active, glacier-cored, tongue-shaped rock glacier. Arr-5, Arr-6, and Arr-8 were not examined in the field.

onization of fresh substrates is estimated to require ~30 years (Calkin and Ellis, 1980; W.P. Brosgé, pers. comm. 1980). The maximum diameter of the largest thallus was used in establishing an age of substrate stabilization, as it was assumed to be the oldest and to possess the optimum growth rate for the site being mapped (Beschel, 1961). The limitations of the method are numerous (Benedict, 1967; Webber and Andrews, 1973; Haerberli *et al.*, 1979), but it has proved to be a useful tool for dating Holocene moraines in many arctic and alpine areas (Beschel, 1961; Andrews and Webber, 1964; Denton and Karlén, 1973; Calkin and Ellis, 1980).

CIRQUE-GLACIER CHARACTERISTICS

The 11 glaciers studied in the Arrigetch Peaks display surfaces with average slopes of 16° and relatively debris-free areas averaging 0.4 km² (Fig. 3; Table 3). Median glacier altitude ranges from 1300 to 1750 m (Fig. 4). The ice bodies have a mean aspect of 010° with an extremely asymmetric strength of 83% (Fig. 5). Headwall aspects are less asymmetric, having a strength of 70% about a mean of 009°.

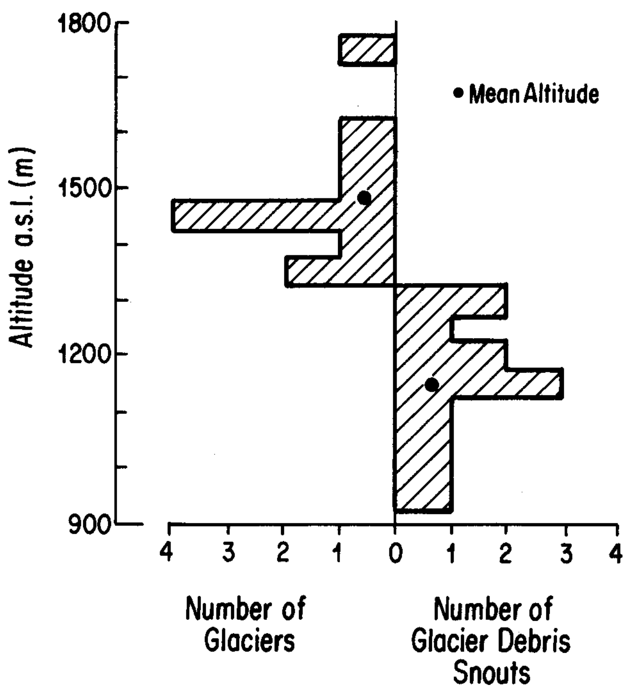

FIG. 4. Summary of altitudinal distributions for glaciers and their associated debris snouts.

The reduction in direct solar radiation due to topographic screening was measured at seven sites on relatively debris-free glacier surfaces (Table 4, Fig. 2). The duration of sunshine on a typical ablation day (~24 July) at the glacier snouts ranged from 1.5 to 14.6 hours. The combined effects of screening, aspect, and slope cause six of the glacier snouts to receive only 52-84% of the potential direct-radiation energy (100%) available to unscreened, horizontal surfaces at this latitude. Cirque glacier Arr-7 receives ~1% of the available radiation energy.

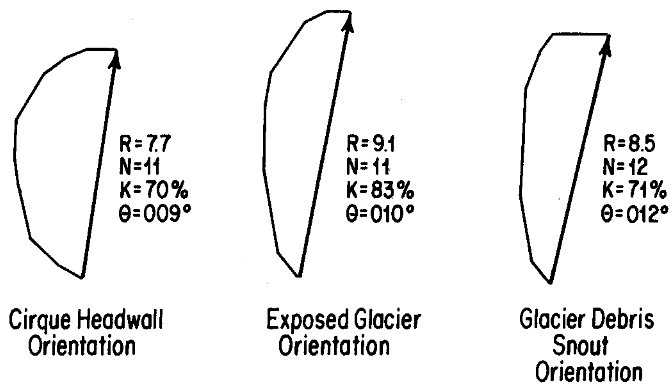

FIG. 5. Graphic summary of aspect distribution data for cirque headwalls; their glaciers; and associated downslope debris snouts. Mean vector (K) shown by the thickened arrow. The strength of the mean vector equals the length of the resultant (R) divided by the total length of the individual vectors (N). The mean orientation of each distribution is shown by Θ and was determined by vector summation.

CIRQUE-GLACIER DEPOSITS

Distinct lobes of debris associated with Holocene glaciation occur downslope of the 11 Arrigetch cirque glaciers (Fig. 2). An assessment of surface stability is critical for mapping and for interpretation of the lichen record preserved on these deposits. The deposits, ranging in area from 0.05 to 1.55 km², are extensively glacier cored (Table 3). At least one of the debris lobes (Arr-7) is a rock glacier rather than a glacier-cored moraine based on the appearance of its surface and terminus. It shows clear evidence of *en masse* downvalley movement (Østrem, 1974; Luckman and Crockett, 1978). Glacier-cored portions of 65-80% of the Neoglacial morainal area in the Arrigetch, and almost 20% of the headward debris portion of the Arr-7 rock glacier, are topographically depressed, actively subsiding, and therefore generally lichen-free.

The snouts of the debris lobes are oriented with strong asymmetry about 012° (Fig. 5). However, they show somewhat weaker asymmetry than the glaciers, suggesting decreased sensitivity to direct radiation. Insolation is further reduced on debris lobes through topographic screening, debris cover, and landform surface slope (Table 4). In order to examine relations between topographic screening of solar energy and deposit type, horizons were measured on debris snouts of four glacier-cored moraines, on the single glacier-cored rock glacier, and on a moraine not cored by glacial ice. The five glacier-cored sites (S-8 to -12, Table 4) are extremely well shaded, receiving only a mean of 7.2 hours of sunshine. This corresponds to 56% of the solar energy available to an unscreened, horizontal surface. In contrast, the non-glacier-cored site (S-4) receives 12 hours of sunshine or 81% of the potential solar energy.

TABLE 4. Duration of direct solar radiation and solar energy received by glacial landforms during part of the ablation season

Survey No.[a] (S-)	Glacier No.[a] (Arr-)	Survey Site Type[b]	Altitude (m)	Exposure[c] Aspect	Exposure[c] Slope (°)	Screening[d] Duration (hours)	Screening[d] Energy Received (%)	Total Energy Received[e] (%)
1	4	GB	1400	N	10	12.2	79.8	78.8
2	11	GB	1450	N	10	12.4	83.9	82.9
3	10	G/BCM & GCM	1250	N	20/0	14.7	89.4	84.4/89.4
4	9	BCM/G	1250	N	10	12.2	81.3	80.3
5	9	G/GCM	1300	N	10	8.2	62.4	61.4
6	1	G/GCM	1350	N	10	13.2	85.6	84.6
7	3	G/GCM	1300	N	10	10.1	76.1	75.1
8	10	GCM/G	1150	N	20	8.7	57.2	52.2
9	2, 3, 4	GCM	950	N	10	5.4	56.2	53.2
10	4	GCM	1200	N	20	6.6	58.2	53.2
11	11	GCM	1050	N	20	11.4	53.1	48.1
12	7	TRG	1000	NE	10	8.4	58.4	57.4
13	7	GTRG	1300	NE	10	1.5	~1	~1

[a]See Figure 2 for locations.

[b]GB = lower half of an exposed glacier body, G = exposed glacier snout, BCM = ice-cemented/non-glacier-cored moraine snout, GCM = glacier-cored moraine snout, TRG = tongue-shaped rock glacier debris snout, and GTRG = exposed glacier core of tongue-shaped rock glacier. Survey sites joined by slash indicate data obtained at first site, but may generally be applied to a nearby portion of the same cirque glacier landform (designated by the second survey-site type).

[c]See Table 2 for resulting energy loss in percent.

[d]Based on +20° declination at lat. 68°N. The sun's path on this day (~24 July) is superimposed on the horizon of each survey site to determine times of sun appearance and disappearance. Energy received is derived from these times and comparison with that measured on an unscreened, horizontal surface at 68°N (considered as 100%; Kondratyev, 1973).

[e]Combined effects of aspect, slope, and screening on reception of direct radiation at each landform-survey site, as determined from summation of energy percentages in c and d. Indicates the percent of direct radiation received at each landform as compared to the energy received on an unscreened, horizontal surface at lat. 68°N.

COMPARATIVE PHOTOGRAPHS

Two camera stations occupied in 1911 and 1962 (Hamilton, 1965a) were reoccupied in 1979 (Figs. 6 and 7). Much glaciologic and glacial-geologic information can be drawn from these photographs. This study considers only those aspects important to lichenometric mapping.

FIG. 6. View south-southwest on 15 August 1979 toward combined terminal moraine of Arr-2, Arr-3, and Arr-4 from camera station 1-62 on the floodplain of Arrigetch Creek (see Hamilton, 1965a, for matching 1911 and 1962 photographs).

The interior of the combined glacier-cored moraine at the terminus of glaciers Arr-2, Arr-3, and the west arm of Arr-4 subsided appreciably from 1962 to 1979. This subsidence is especially apparent upslope of the terminal ridges on the east (left-hand side, Fig. 6) where the glacier core is clearly exposed. More intense subsidence is recorded for the 51-year interval between 1911 and 1962. However, the distinct lateral and terminal ridges at the perimeter of this lobe in 1911, 1962 and 1979 photographs from station 1-62 support overall stability along the margin during the 20th century. Stability is also indicated by the dark tonal quality of this margin, imparted by a widespread cover of the aerial green algae with hematochromatic pigment identified by R. Zander (pers. comm. 1980) as *Trentepohlia iolithus* (L.) Wallr. This cover intensified from 1911 to 1962, perhaps with algal colonization of the granitic sub-strate, but it has remained relatively uniform since 1962. The maintenance of peripheral stability despite the collapse of the interior glacier core is favorable for lichenometric dating, which depends on substrate stability.

At glacier Arr-4 the area deglaciated since 1911 is approximately delineated on Figure 7. A bedrock divide marked by a glacial spillway (S) separates Arr-4's east and west arms. This spillway was ice- or snow-filled in 1911. In 1962

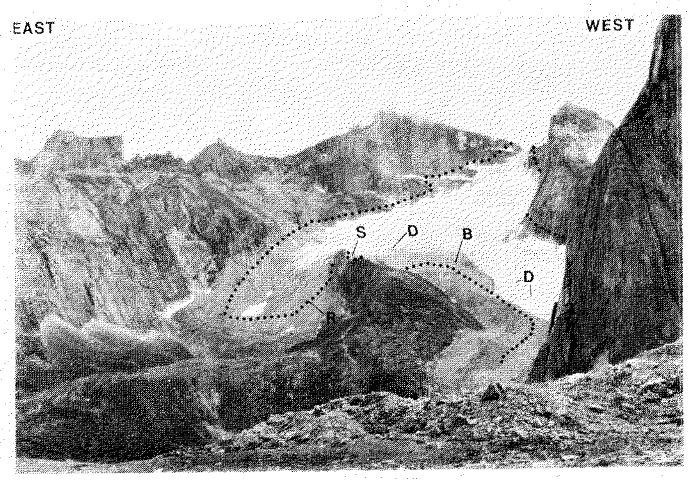

FIG. 7. View southeast on 15 August 1979 toward east glacier arm and associated moraine of Arr-4 from camera station 2-62 on the threshold of a hanging cirque (see Hamilton, 1965a, for matching 1911 and 1962 photographs). Note glacial spillway (S); stable, bedrock-cored debris (B); large boulder, ice-covered in 1911 (R); and englacial/supraglacial debris (D). Dotted line shows approximate ice margin in 1911.

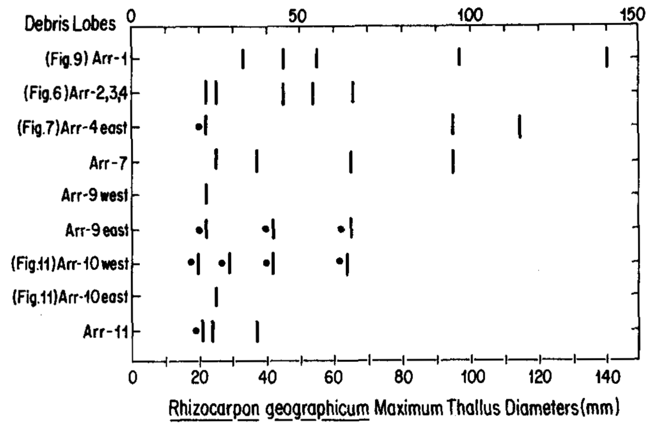

FIG. 8. Maximum *Rhizocarpon geographicum* thallus diameters associated with the nine lichenometrically-mapped debris lobes. Bedrock-cored or ice-cemented moraine ridges shown by (•); the remaining surfaces were glacier-cored. See Fig. 2 for location of debris lobes.

and 1979 the ice margin was well upslope of this spillway. A thin, bedrock-cored veneer of glacial drift left on the divide and along the interlobate area (B) provides an optimum substrate for lichenometric measurements.

Hamilton (1965a) estimated that both arms of Arr-4 retreated 200 m upvalley and 100 m higher (in altitude) during the period from 1911 to 1962. Glacial recession and thinning continued to 1979 but probably at a slower rate. The ice margin of Arr-4 displays approximately the same amount and location of supraglacial debris in 1979 (D, Fig. 7) as in 1962. West of the spillway (S on Fig. 7) the ice margin retreated 10 m from 1962 to 1979. East of the spillway the glacier tongue retreated upvalley less than 50 m, becoming partly covered with englacial and talus debris between 1962 and 1979. A light tonal quality implying instability prevails over most of the deposit downslope of this eastern tongue. However, at least one large boulder (R) within this deposit did not move noticeably between 1962 and 1979.

LICHENOMETRIC MAPPING OF DEBRIS LOBES

Six depositional complexes were mapped; these form nine distinct debris lobes downslope of glaciers (Figs. 2 and 8). Downslope from the glacier termini lichens are locally sparse. The lichen diameters are most consistent on marginal morainal ridges, especially on thin drift that lacks ice cores. Here the largest lichen diameters were associated with the most distal portions of the deposits. The destabilizing effects of melting glacier-ice cores cause lichens to be sparse and inconsistent in size. The ubiquitous *Trentepohlia iolithus* algae may further inhibit lichen cover as it precedes lichen colonization (D. Cooper, pers. comm. 1980).

We have grouped our *R. geographicum* s.l. distribution data to show glacial drift surfaces hosting lichens of similar maximum diameter in Figure 8. The similarity of these lichen diameters on morainal ridges of several glaciers suggests that the surfaces stabilized about the same time. In the following summation all thallus measurements refer to *R. geographicum*.

FIG. 9. Preserved distal ridge along northwest lateral moraine of Arr-1, lichenometrically dated at (L) 4400 ± 900 yr B.P. Abutting ridge to right hosted sparse 27-33 mm *Rhizocarpon geographicum*.

The most dense and diverse vegetation associated with a moraine occurred on the margin of Arr-1 debris lobe (Figs. 2 and 9). This area also hosted the largest lichen found on cirque-glacier debris lobes in the Arrigetch Peaks. It had a maximum diameter of 141 mm.

The most complete lichenometric records on the debris lobes of Arr-2, 3, and 4 (Fig. 6) were along the western lateral margin on topographically-prominent surfaces and on an interlobate area in front of Arr-4 (Fig. 7). A recent glacial maximum is recorded by 22-mm thalli about 150 m from the glacial margin. No lichens were found within

15 m of the ice margin (Fig. 10); this distance may represent deglaciation during the ~30 years required for lichen colonization. Southwest of the glacial spillway (S, Fig. 7), thalli progressively increase downslope toward the 1911 ice-marginal position (B, Fig. 7); thalli attain a maximum diameter of 11 mm, and lichen cover on individual boulders approaches 15%. The glacier-cored moraine east of the spillway is nearly devoid of lichens, except along the margin where terminal ridges bear thalli up to 115 mm. *R. geographicum* thalli in excess of 250 mm were found downslope of this cirque-glacier deposit along the cirque threshold.

The lichenometric record on the actively flowing rock glacier (Arr-7) was difficult to map and interpret. The

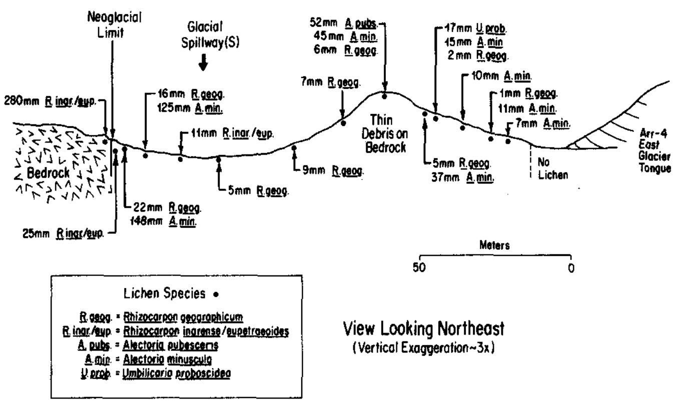

FIG. 10. Field sketch of deglaciated bedrock divide downslope of Arr-4's interlobate ice margin, looking northeast at glacial spillway (S) shown in Fig. 7. The *Alectoria* and *Umbilicaria* species listed grow approximately 7× faster than the *Rhizocarpon* species. Note exceptionally large size of *Rhizocarpon* thallus just beyond the maximum Neoglacial limit, which is defined by 22-mm *R. geographicum*; and the very high percentage of ≤16-mm *R. geographicum* characterizing the divide.

upper two-thirds of the rock glacier surface (<1 km from headwall), noticeably fresher and more unstable than the lower one-third, hosted sparse zones of ≤37-mm thalli. In the lower part, numerous stable ridges appear to be defined by 65- and 95-mm lichen thalli.

Two ice tongues emanate from Arr-9. Bedrock-cored distal ridges in the interlobate area were characterized by maximum thalli of 22, 42, and 65 mm. Arr-10 also has two debris lobes (Fig. 11). The westernmost lateral ridge is glacier-cored and bears patches of 20- and 42-mm lichens. The outer margin of the non-glacier-cored moraine (BCM, Fig. 11) displayed nested ridges bearing 22-, 42-, and 64-mm thalli in outward succession. The western ice lobe of Arr-10 has retreated 200 to 300 m from the terminal moraine that bears 22-mm thalli. The only consistent lichen diameter pattern on the eastern glacier-cored moraine of Arr-10 was 25 mm on a medial ridge system. In addition, at Arr-11 maximum 20-mm lichens cover bedrock-cored debris in two east-flowing glacial spillways.

A unique aspect of the lichenometric record of the Arrigetch Peaks, as compared with deposits of cirque glaciers observed elsewhere in the central Brooks Range (Calkin and Ellis, 1980), is the occurrence of thin drift sheets directly on bedrock behind terminal moraines characterized by ~22-mm *R. geographicum* thalli. This allows determination of deglaciation rates from this last major advance.

LICHENOMETRIC CHRONOLOGY

Material datable by the radiocarbon method has not yet been found associated with cirque-glacier deposits in the Arrigetch Peaks. To derive an absolute chronology of past

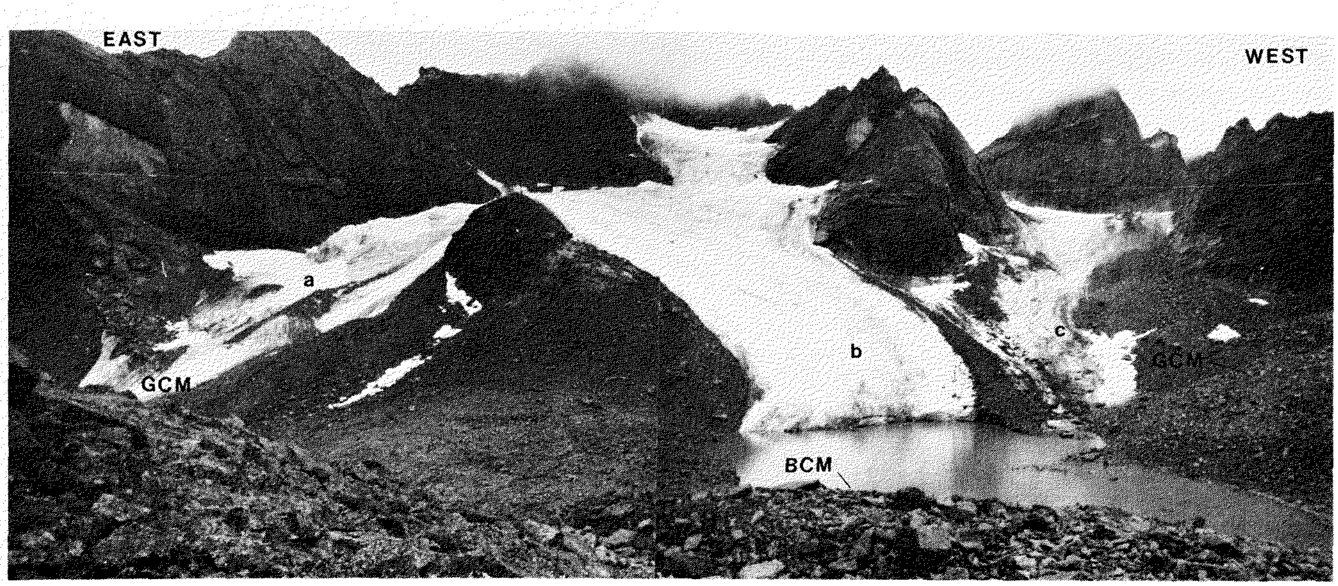

FIG. 11. View south toward cirque glacier complex Arr-10. Note glacier-cored moraine (GCM) downslope of ice tongues (a) and (c), and bedrock-cored, ice-cemented moraine (BCM) downslope of (b). S. Walti in right foreground stands along the maximum moraine boundary for Neoglacial expansions.

glacial activity in this area, it is necessary to relate lichen diameters to ages determined elsewhere in the central Brooks Range. This is done by using the *Rhizocarpon geographicum* s.l. growth curve developed for the Atigun Pass area, where mean annual temperature is about −14°C (Calkin and Ellis, 1980).

The Atigun Pass curve has radiocarbon-dated control points from 320 ± 100 to 1300 ± 100 yr B.P. (the latter control point based on sample BGS 670, Calkin and Ellis, unpub. data 1980), which indicate a *linear* growth phase approximating 3 mm per century following a 200-year *great growth* period (Fig. 12). The curve resembles the more well-controlled *R. geographicum* growth curve for Baffin Island, probably because both regions have similar climatic regimes (Andrews and Webber, 1964; Andrews and Barnett, 1979; Calkin and Ellis, 1980). Meager climatic data, some of which has been discussed (Table 1), suggest the Arrigetch Peaks area is slightly warmer and wetter than the Atigun Pass area. This climatic difference may make ages derived from Arrigetch lichen diameters too old when correlated to the growth curve based largely on Atigun Pass data (Beschel, 1961). We estimate the growth curve to have a ± 20% age reliability. This estimate of age accuracy is speculative, but is included to emphasize the limitations of lichenometric dates (Miller and Andrews, 1972). The growth curve is calibrated in radiocarbon years.

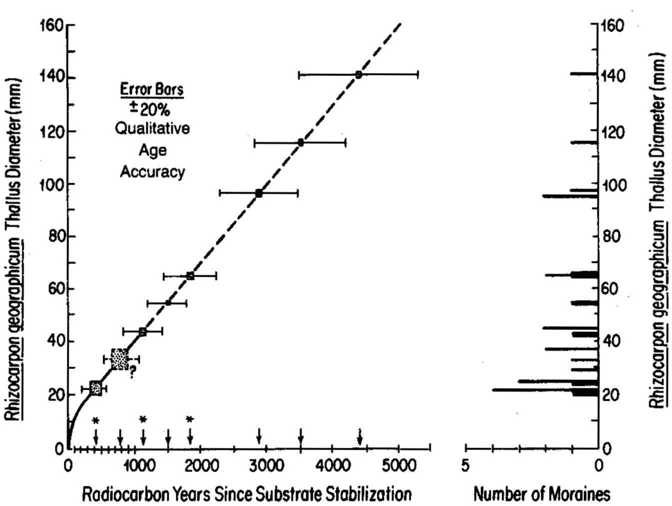

FIG. 12. *Rhizocarpon geographicum* growth curve for the central Brooks Range (after Calkin and Ellis, 1980) correlated with the frequency histogram of maximum thallus diameters found in deposits associated with eight cirque glaciers in the Arrigetch Peaks (see Fig. 8). Clusters of similar-size thalli from this histogram are shown on the growth curve as shaded rectangles with estimated ±20% age-reliability error bars. These rectangles are drawn proportional to the range of thallus sizes in each cluster. Arrows along growth curve abscissa point to mean age of the eight *R. geographicum* size concentrations. Starred arrows indicated relatively well-established events. The curve is not fixed to any given year. To convert radiocarbon age given on the abscissa to radiocarbon yr B.P. (before A.D. 1950), subtract A.D. 1950 from the current A.D. date, and deduct this value from the graph's radiocarbon age.

Mapped clusters of maximum thallus diameters from the Arrigetch glacial debris lobes are reported as actual thalli-mm range and the derived mean age as determined from the curve. The ± 20% age reliability takes into consideration the low and high values in the size cluster. To clearly delineate the age as lichenometrically determined, (L) is placed before the mean value in the text below. Conversions of radiocarbon B.P. ages to A.D. ages follow the correction curve in Oeschger (1975, Fig. 6).

The *R. geographicum* diameters found to characterize the nine debris lobes (Fig. 8) can be grouped into eight clusters corresponding to derived mean age ± 20% as follows:

20-25 mm	(L)390 ± 90 yr. B.P.	A.D. 1410-1600
29-37	540 − 870 (±20%)	
42-45	1120 ± 300	
54-55	1500 ± 300	
64-66	1800 ± 400	
95-97	2850 ± 600	
115	3500 ± 700	
141	4400 ± 900	

Ages derived from the lichen growth curve date the beginning of glacial retreat from advanced ice positions and stabilization of debris ridges (Andrews and Barnett, 1979), not strictly the times of maximum glacier expansions and ridge construction.

The most recent major glacial expansion was well represented by extensive ridges dated as (L) 390 ± 90 yr B.P. or about A.D. 1410-1600. It either obliterated or at least disturbed large segments of the older lichenometric record. Bedrock-cored debris between these ridges and the glacier snouts of Arr-4 and Arr-10 indicates that initial recession from the maximum was slow, the ice margins remaining close to the maximum extent until ~(L) 170 ± 40 yr B.P. or about A.D. 1640-1750, when marked recession commenced. Smith's 1911 photograph and lichenometric mapping of Arr-4's deposit suggest deglaciation was most rapid after A.D. 1870. However, only ~15 m of retreat has occurred here in the past 30 years.

The next most commonly preserved lichenometric pattern is interpreted to represent two major glacial expansions dated at (L) 1120 ± 300 and 1800 ± 400 yr B.P. This evidence was found on debris ridges downslope of three glaciers. At two of the glaciers, these continuous ridge systems were very stable, bedrock-cored, and nested with moraines from the most recent expansion. Discontinuous glacier-cored surfaces on four debris lobes indicate less well-defined glacial activity occurring about (L) 540-870 (±20%) yr B.P. These data may relate more to varying degrees of surface stability than to times of glacial growth.

Evidence for major activity of cirque glaciers prior to (L) 2000 yr B.P. occurs beyond the ridges considered here as stable patches of drift bearing lichens that indicate ages to (L) 4400 ± 900 yr B.P. Interpretation and dating of these drift patches is difficult due to poor geomorphic expression along debris-lobe margins and uncertainties with the older part of the lichen growth curve. However, several moraines in the Atigun Pass area display similar-sized *R. geographicum* indicating cirque-glacier advances earlier than 2000 yr B.P. (Calkin and Ellis, 1980).

DISCUSSION

Comparison of cirque glaciers in the Arrigetch Peaks with 133 glaciers analyzed near Atigun Pass (Ellis and Calkin, 1979) shows the upper and lower size limits and average surface slopes of the ice bodies to be similar. Also, glaciers in the Arrigetch Peaks are oriented to minimize insolation, as are glaciers elsewhere in the Brooks Range (Wendler, 1969; Ellis and Calkin, 1979). This reflects marginal conditions for glacierization during Holocene time.

Despite the similarities, the moraines within the Arrigetch Peaks are much less stable and more extensively glacier-cored that those in the Atigun Pass area. The glacier-cored moraine in Figure 6, for example, reaches down to 950 m altitude, some 350 m lower than the lowest probable glacier-cored deposit near Atigun Pass. The lower altitudes of glaciers in the Arrigetch Peaks and their deposits (Fig. 4) may be partly explained by their more pronounced topographic screening and the resulting larger reduction in direct-radiation energy which they sustain. Differences in the amount of direct radiation received may also partly explain why moraines cored with glaciers dominate over ones without such cores. The effects of probable greater annual precipitation and cloudiness on the formation of the more westerly Arrigetch moraines as compared with those of the Atigun Pass area are unkown.

The relative importance of debris supply (Whalley, 1974; Griffey and Whalley, 1979) and topographic shading in maintaining glacier-cored deposits is shown by the relations between the two ice tongues of glacier Arr-10 (Fig. 11). The moraine downslope of the eastern tongue (*a* in Fig. 11) is glacier-cored. It occupies a depositional environment where only 52% of the potential solar radiation is received (S-8, Table 4) and input of supraglacial debris is high. The drift downslope of ice tongue *b* (Fig. 11) received 89% of the potential direct-radiation energy on 24 July (S-3, Table 4). Its debris input is low and there is no glacier core under the moraine. Although the lateral moraine downslope of the western glacier tongue *c* also receives ~89% of the available solar energy, it remains cored with glacier ice, apparently because of a high input of supraglacial debris from the adjoining cirque sidewall. Other glaciers, such as Arr-11 and the east arm of Arr-4 (Fig. 7), have relatively debris-free surfaces; but minimal solar energy in the depositional environments during the ablation season (53 and 49% on 24 July) may account for glacier-cored moraines there. The small accumulation of glacial drift in the interlobate area of Arr-4 (Fig. 7) does not favor earlier times of markedly-increased debris supply. Apparently glacier-cored moraines can form in environments with minimal solar energy and low to high input of debris, or high inputs of *both* solar energy and debris. In contrast, moraines deposited without ice cores require low input of debris and receipt of a substantial portion of the potential solar energy.

Formation of the rock glacier lobe of Arr-7 apparently requires more extreme environmental conditions than those favoring stationary, glacier-cored moraines. Precipitously steep cirque walls rising 600 m above this feature allow only 1% of the sun's energy to reach the headward portion of this landform during a typical part of the ablation season. In addition, the steep walls furnish a high volume of debris to the glacier-rock glacier system (Whalley, 1974).

Lichenometric correlations between debris lobes of varying stability within a given area should be viewed with caution because of assumed differences in colonization times. However, similar-sized thalli characterize morainal ridges in the Arrigetch Peaks (Fig. 8) because: a) the ice masses reacted synchronously to climatic changes; b) lichen colonization times do not vary significantly with substrate instability; and/or c) the lichenometric method is too imprecise to distinguish colonization differences.

A brief review of other climatic indicators corroborates the lichenometric chronology presented in this paper. Hamilton (1965b, Fig. 9) interprets a composite Alaskan temperature record as showing a net 1°C rise from the 1800s to A.D. 1941, followed by decreasing mean annual temperature. Garfinkel and Brubaker (1980) suggest a rise of ~2°C from A.D. 1830 based on tree-ring data from the Alatna River valley (Fig. 1). Tree line chronologies for the Noatak and Arrigetch valleys suggest that cold spells occurred in the mid-1500s and late 1600s and warming conditions from the late 1800s to the 1900s (G. Jacobi, pers. comm. 1979). Rates of forest growth in central Alaska were depressed during several distinct intervals, notably the mid-1600s and early 1800s (Haugen and Brown, 1978). The times of depressed tree growth correlate with the lichen-dated interval A.D. 1410 to 1750, when at least some glaciers in the central Brooks Range were near their maximum extension.

Radiocarbon dates from valleys of the central Brooks Range suggest that glaciers were absent or relatively small during middle Holocene time (Hamilton, 1980b). Apparent intensification of cold-climate processes about 3500 yr B.P. led to increased sediment yield to mountain valleys. This caused terrace alluviation, especially in the heads of valleys that originate in cirques occupied by glaciers.

CONCLUSIONS

Our study of Holocene glaciation of the Arrigetch Peaks area shows that:

1) The cirque glaciers of the Arrigetch Peaks are morphologically similar to those found in east-central Brooks Range, but associated deposits are much more unstable and most are cored with glacier ice.
2) Glacier-cored moraines in the Arrigetch area are extremely well shaded by surrounding terrain. They receive only a mean of 7.2 hours of sunshine during a typical part of the ablation season (~24 July). This corresponds to 56% of the direct-radiation energy available to an unscreened, horizontal surface.
3) Matching sets of glacier photographs dating from 1911 confirm that terminal and lateral moraine ridges bordering glacier-cored drift bodies are relatively stable, in contrast to collapsing interiors. These photographs, combined with lichenometric mapping of bedrock-cored debris, demonstrate that marginal recession from the last major glacial advance was 150 to 300 m. Recession was most rapid after A.D. 1870 and decelerated after the mid-1900s.
4) Three major expansions of late Holocene cirque glaciers are relatively well established by geomorphology and lichenometry in the Arrigetch area. These are dated lichenometrically (estimated ±20% age reliability) as 390 ± 90, 1120 ± 300, and 1800 ± 400 radiocarbon yr B.P.

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